International Journal of Heat and Mass Transfer 56 (2013) 667–673

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of die exit geometry on *internal die drool* phenomenon during linear HDPE melt extrusion

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ARTICLE INFO

Article history:
Received 26 July 2012
Accepted 26 September 2012
Available online 27 October 2012

Keywords:
Mass transfer
Flow induced molecular weight fractionation
Die drool phenomenon
Die buildup
Flow instabilities
Extrusion
Polymer melt
Rheology

ABSTRACT

In this work, the effect of die exit design on the *internal die drool* phenomenon occurring during extrusion of HDPE has been experimentally investigated. It has been revealed, that firstly, the effect of flared length and die exit angle on the *internal die drool* intensity during extrusion of HDPE has non-monotonic character and secondly, flared dies are more stabilizing in comparison with chamfered dies. It has been suggested that suppression mechanism of the *internal die drool* phenomenon through die exit modification can be understood through the balance between the melt pressure/normal stresses at the die exit, adhesion at metal wall/flowing melt interface and extensional stress induced by the extrudate draw off, which can lead to flow situation at which low molecular weight species are effectively removed from the die exit region by the moving extrudate and only small portion of them remains at the die exit face.

1. Introduction

During extrusion process, there is a tendency for some of the extruded polymer materials to adhere to exit edges or open faces of extrusion die from which the extruded material emerges. The material so deposited on the die exit, can build up into a large compact usually degraded mass or can form drips, flakes or powder which frequently break away from the die, adhere perseveringly onto extruded product surface and thus damage it. This effect is in extrusion art defined as undesirable spontaneous accumulation of polymer melt at the die exit face and it is termed like "*die drool*", "*drooling*", "*die lip build-up*", "*die bleed*", "*die plate-out*", "*die deposit*", "*die drip*" or "*die moustache*" and the accumulated material is generally named "*drool*" [1,2].

Die drool phenomenon can appear in all common extrusion techniques like pipe and profile extrusion, film casting, fibre spinning, film blowing, or cable sheathing. In some of these techniques, *drool* can adhere not only to the outside faces but also to the inside ones which makes simple cleaning procedure based on manually collecting of *drool* mass from the die exit face virtually impossible. Then, only one way consists in periodic stops the extrusion line, disassembling of all extrusion die parts and their mechanical cleaning remains. Clearly, this procedure is time and also money consuming.

Historically, one of the original remarks about "...difficulty in the extrusion of thermoplastic resins because of adhesion of hot thermoplastic resin to the extrusion die and, occasionally, because of die corrosion from small amounts of heat decomposition products from the resins" can be found in US Patent from 1946 [3] and probably firstly used term "*drooling*" in writing form could be found in the patent of Foster in 1958 [4]. During the years, extrusion experts and researches tried many ways to suppress *die drool* widely described in patents and research papers. They tested inside or outside extrusion die edges design changes [4–10], extruded polymer melts modifications [11–16] and also processing conditions changes [2,17–18]. However, no experimental method has been found to be universal; each of them can be used only for particular polymer material and extrusion process/extrusion die. Furthermore, in some patents authors even speculated that *drooling* can be caused by "...incompatibility of polymer with certain other substances mixed with it before extrusion" (1960, [12]), "...the sudden release of pressure on the polymer material as it emerges from the die into the atmosphere" (1964, [6]) or "...part of the fillers, such as clay, which...may be forced out of the matrix at the point of highest extrusion pressure which is a point along the extruder die area" (1971, [13]). Later, some papers in which authors searched *die drool* formation mechanism have

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.09.059

been published [1,2,10,16,19–23]. It is generally accepted that there are two types of the *die drool* phenomenon; "*external die drool* phenomenon", which is generated just at the end of the die due to the extrudate free surface creation and negative pressure generation (causing the suction effect) [2,10] and "*internal die drool* phenomenon", which is initiated inside the processing equipment as the results of degradation [22] or flow induced molecular weight fractionation [16]. In fact, there is number of material, processing and die design based parameters promoting and suppressing the *die drool* phenomenon and some of them have been recently documented such as pressure fluctuations in screw [19], volatiles, low molecular fractions of the polymer, fillers, poor dispersion of pigments [24], *die swell* [19,22], processing near degradation temperature [23,25], dissimilar viscosities in blends [26], broadening molecular weight distribution [27–28], increasing melt elasticity [16,23], *shark skin* [2,10], *slip-stick* phenomenon [16,28–29], or abrupt corners at the die lips [7,8,10] have been found to promote *die drool*. On the other hand, chain branching increase [16], polymer processing aids addition [26], using ceramics dies [30] or dies with PTFE chemically/physically locked in die wall [24], silicon rubber coated surface of extrusion die [29], hard chrome dies [31], flared [7,8,10] or chamfered [10] die exits, have been found to reduce this phenomenon. With respect to the stabilizing role of the die design, it was initially believed that flared dies are so effective due to occurrence of stress undershoot inside flared section [1]. However, Ding et al. [9] mathematically modeled stress field inside the flared section and they concluded that stress undershoot is not the main reason for suppressing accumulation of *drool* mass at the die lips. They have suggested that the history of the stresses upstream of the exit, not just their instantaneous values at die lips, governs the *die drool* reduction in flared dies. Recently, Chaloupkova and Zatloukal [10] were able to correlate stabilizing efficiency of die exit chamfering, die opening and die exit flaring with negative pressure, pressure gradient and normal component of the pressure gradient during extrusion of the metallocene based LLDPE at which the *external die drool* has occurred.

In this work, experimental analysis has been performed for extrusion dies at which chamfer angle and flared length were systematically varied in order to understand the role of die design for the internal type of *die drool* phenomenon as well as to explore the knowledge about parameters which could allow more efficient die design optimization.

2. Experimental

In this work, well stabilized unfilled virtually linear HDPE polymer melt (*HDPE Liten FB 29 E2009 3220 4479*, extrusion grade, Unipetrol RPA, Czech Republic, material characterization is summarized in our previous work [28]) has been used.

The *internal die drool* measurements were performed on specially designed extrusion line equipped by replaceable capillary (see Fig. 1), which has already been used in our previous studies [16,23,28]. The line was consisted of conventional *Plasti – Corder 2000* model (Brabender, Germany) single-screw extruder with diameter $D = 30$ mm and $L = 25D$ (standard single-thread screw with compression ratio 4:1, and lengths of zones: *feed* $L_1 = 10D$, *compression* $L_2 = 3D$, *metering* $L_3 = 12D$), transition annular part, specially designed annular extrusion die, photo camera *Canon 600D* model (Canon, Inc., Japan) with resolution of 18 Mpx equipped with Canon macro lens EF 100 mm placed near the die exit for *die drool* visualization and finally draw-off mechanism.

The *die drool* experiments were performed as follows. Extruder zones (from the hopper to the die) were heated to $T_1 = 150$ °C, $T_2 = 155$ °C, $T_3 = 160$ °C and $T_4 = 160$ °C, respectively by keeping the annular tube (connecting die and extruder) and die exit temperature constant, $T_5 = T_6 = 160$ °C. The low exiting temperature 160 °C for the HDPE melt was chosen to achieve highly pronounced fractionation effect due to high efficiency of melt to store elastic energy as well as to suppress any thermal/oxidative degradation. Further, mass flow rate (MFR) was chosen 750 g h^{-1} (apparent shear rate 673 s^{-1}) to ensure that the flow condition lies above the *slip-stick* phenomenon, i.e. in the "*superflow*" regime at which the *die drool* intensity is the highest as shown in [28]. In order to measure fractionated (*drooled*) polymer mass accumulated at the die exit, the following methodology was used. The extruder was stopped after 10 min of extrusion and the accumulated material was carefully manually removed from the die lip by a tweezer, weighted on a sensitive analytical balance and the procedure was repeated three times for each capillary to calculate standard deviation. Before each set of three independent 10 min tests (for given capillary), barrel, screw and all parts of the die have been disassembled and perfectly manually cleaned. Finally, *die drool* intensity has been expressed in dimensionless form through buildup ratio *BR* (introduced by Gander and Giacomin in [1]):

$$BR = \frac{\dot{B}}{\dot{m}} \tag{1}$$

where $\dot{m}$ is total mass flow rate of extruded polymer melt and $\dot{B}$ means buildup rate:

$$\dot{B} = \frac{B}{t_e} \tag{2}$$

where B is the mass of accumulated *die drool* material on the die exit face and t_e is total extrusion time of each test (10 min in our case).

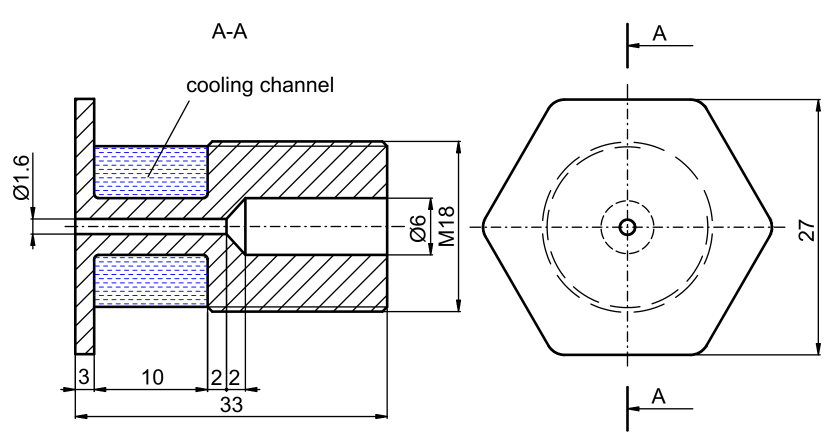

Fig. 1. Section view of basic replaceable capillary die with dimensions.